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# Retrieval Induces Forgetting, But Only When Nontested Items Compete for Retrieval: Implication for Interference, Inhibition, and Context Reinstatement

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**Abstract**

The mechanism responsible for retrieval-induced forgetting has been the subject of rigorous theoretical debate, with some researchers postulating that retrieval-induced forgetting can be explained by interference ( J. G .W. Raaijmakers & E. Jakab, 2013) or context reinstatement (T. R. Jonker, P. Seli, & C. M. MacLeod, 2013), whereas others claim that retrieval-induced forgetting is better explained by inhibition (M. C. Anderson, 2003). A fundamental assumption of the inhibition account is that nonpracticed items are suppressed because they compete for retrieval during initial testing. In the current study, we manipulated competition in a novel interpolated testing paradigm by having subjects learn the nonpracticed items either before (high-competition condition) or after (low-competition condition) they practiced retrieval of the target items. We found retrieval-induced forgetting for the nonpracticed competitors only when they were studied before retrieval practice. This result provides support for a critical assumption of the inhibition account.

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Matthew Erdman, who is now at Trane (Ingersoll Rand), collected the data from Experiments 1 and 2 as part of his dissertation. The data from Experiments 3 were 4 were collected by Sara Davis. Jason Chan wrote the manuscript.

**Abstract**

The mechanism responsible for retrieval-induced forgetting has been the subject of rigorous theoretical debate, with some researchers postulating that retrieval-induced forgetting can be explained by interference (Raaijmakers & Jakab, 2013) or context reinstatement (Jonker, Seli, & MacLeod, 2013), whereas others claim that retrieval-induced forgetting is better explained by inhibition (Anderson, 2003). A fundamental assumption of the inhibition account is that nonpracticed items are suppressed because they compete for retrieval during initial testing. In the current study, we manipulated competition in a novel interpolated testing paradigm by having subjects learn the nonpracticed items either before (High-Competition) or after (Low-Competition) they practiced retrieval of the target items. We found retrieval-induced forgetting for the nonpracticed competitors only when they were studied before retrieval practice. This result provides support of a critical assumption of the inhibition account. We also considered the educational implications of this finding.

# Retrieval Induces Forgetting, But Only When Nontested Items Compete for Retrieval: Implications for Interference, Inhibition, and Context Reinstatement

Retrieval has often played an underappreciated role in the history in memory research (Schacter, Eich, & Tulving, 1978). Before Tulving's seminal work on encoding specificity (Tulving & Thompson, 1973), the determinants of memory performance were often attributed to various operations that occur during encoding (e.g., repetition, distributed learning, deep processing). However, extensive research over the past decades has shown that retrieval has a profound influence on what is remembered (Chan & LaPaglia, 2013). In the present paper, we focus on the phenomenon of retrieval-induced forgetting, wherein practicing retrieval on a subset of studied materials can enhance subsequent recall of the tested material (Carpenter, 2012; Delaney, Verkoeijen, & Spirgel, 2010; Roediger & Butler, 2011; Roediger & Karpicke, 2006), but sometimes at the expense of impaired retrieval of the nontested material (Anderson, 2003; Storm & Levy, 2012). Although retrieval-induced forgetting is well documented empirically, the mechanisms that contribute to its occurrence are still being debated (Hulbert, Shivde, & Anderson, 2012; Jonker, Seli, & MacLeod, 2013; Raaijmakers & Jakab, 2013; Storm & Levy, 2012; Verde, 2012).

The effects of performing retrieval practice on subsequent memory has garnered considerable interest over the past decade (Carpenter, 2012; Rawson & Dunlosky, 2011; Roediger & Butler, 2011). This interest stems largely from the appeal of using retrieval practice – a potent memory enhancer – to improve educational practice. It is therefore important to understand the limits and potential negative consequences of retrieval on learning. Moreover, retrieval-induced forgetting provides a window into understanding human forgetting. The theoretical perspective that has generated the most interest and contention is that successful retrieval of a target memory requires active suppression of its competing memory traces (Anderson, Bjork, & Bjork, 1994). That is, forgetting is a consequence of one's attempt to resolve competition. In this study, we sought to provide a direct test of this idea.

In a typical retrieval-induced forgetting experiment, people study category-exemplar pairs (e.g., Fruit - Lemon, Fruit - Banana, Insect - Roach, Insect - Beetle), perform selective retrieval on only some of the pairs from some of the categories (e.g., Fruit - Le_ and none of the items from the Insect category). After what is typically a brief retention interval (5-30 min, but see also Chan, 2009; Chan, McDermott, & Roediger, 2006; M. D. MacLeod & Macrae, 2001; Spitzer, 2014), individuals are tested on all pairs. This procedure produces three types of items: Rp+ refers to items that receive retrieval practice (e.g., Lemon), Rp- refers to nonpracticed items from the practiced categories (e.g., Banana), and Nrp refers to items from the nonpracticed categories (e.g., Roach and Beetle). As expected, Rp+ items are more likely to be recalled than Nrp items – a testing effect – but the key finding for this paradigm is that Rp- items are less likely to be recalled than Nrp items - a retrieval-induced forgetting effect.

Although the empirical basis of retrieval-induced forgetting is well established, its theoretical underpinnings remain under dispute. The two major accounts for retrieval-induced forgetting appeal to two fundamental cognitive processes: competitive interference and inhibition.[1] Based on traditional interference theories, some researchers (Raaijmakers & Jakab, 2013; Verde, 2013) argue that selective retrieval of the Rp+ exemplars increases their item

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[1] In a recent paper, Jonker and MacLeod (2013) proposed a context account that provides an alternative explanation for retrieval-induced forgetting. We address this account in more detail in the General Discussion.

strength and their associative strength with the category name. When the category name reappears later as a retrieval cue, the highly accessible Rp+ exemplars interfere with, or block, retrieval of the nontested Rp- exemplars, thereby reducing their recall likelihood. Anderson and colleagues (Anderson, 2003; Anderson et al., 1994; Storm & Levy, 2012; Wimber et al., 2008), however, offered an alternative explanation of retrieval-induced forgetting that is grounded in the idea of inhibitory processes, whereby successful retrieval practice of the Rp+ items requires inhibition of the nontarget, Rp- items. The core of this idea is that inhibition helps to resolve the competition between the Rp+ and Rp- items, thereby allowing the target (Rp+ item) to be recalled, and retrieval-induced forgetting is the behavioral manifestation of this inhibitory control.

There are two major differences between these accounts on their explanation of retrieval-induced forgetting. First, interference theory suggests that retrieval-induced forgetting occurs because the strengthened Rp+ targets block recall of the Rp- competitors *during the final test*, whereas inhibition theory suggests that retrieval-induced forgetting shows the lingering effects of suppression that occur *during retrieval practice*. Second, interference theory suggests that retrieval practice of the Rp+ items does not have any direct impact on the memory strength of the Rp- competitors, whereas inhibition theory argues that memory strength of the Rp- items is directly weakened through suppression.

## Overview of the main principles in the inhibition theory

In his influential review of the literature, Anderson (2003) outlined four principles of the inhibition theory that distinguishes itself from traditional interference, inhibition-free accounts of forgetting. The four principles are cue independence, strength independence, retrieval dependence, and competition dependence. We briefly describe these four principles here, but the focus of the present paper is on competition dependence. In this overview, we sought to demonstrate that extant investigations have yet to provide an unequivocal test for competition dependence, as they have often conflated multiple principles of the inhibition theory. For explication purposes, we use the term "competition" to describe the retrieval competition that occurs during the retrieval practice phase, and we use "competition dependence" as the name of this assumption. To reduce potential confusion, the term "interference" is used exclusively in the context of traditional interference theory.

*Cue independence* refers to the idea that inhibition directly weakens the memory representation of the Rp- items, so retrieval practice should impair subsequent memory of the nonpracticed exemplars even when the original studied category name is not used as a retrieval cue. *Strength independence* refers to the idea that varying the memory strength of the practiced Rp+ items does not influence the level of retrieval inhibition exerted on their Rp- competitors. This differs from predictions based on interference theory, where greater strengthening of the practiced items should increase their interference at test, thus leading to greater retrieval-induced forgetting. *Retrieval dependence* describes the notion that inhibition of the Rp- items arises when one attempts to recall their Rp+ competitors. As a result, retrieval-induced forgetting should not occur when the Rp+ items are strengthened by means other than retrieval. In contrast, according to interference theory, any practice that increases memory strength of the Rp+ items relative to the Rp- items should produce retrieval-induced forgetting, regardless of whether retrieval is involved. A detailed discussion regarding these assumptions are beyond the scope of the present paper (for reviews, see Anderson, 2003; Murayama, Miyatsu, Buchli, & Storm, 2014; Raaijmakers & Jakab, 2013; Verde, 2012).

*Competition dependence* refers to the idea that inhibition is initiated to resolve competition during retrieval practice. Therefore, only items that compete for retrieval should be susceptible to inhibition. This is a counterintuitive concept as it suggests that Rp- items that are strongly associated with the category cue, and thus more likely to compete for retrieval, should show a larger retrieval-induced forgetting effect than Rp- items that are weakly associated with the category cue. Indeed, predictions based on interference theory would suggest that the opposite should occur; that is, it should be more difficult to block recall of stronger competitors than weaker ones. Competition dependence is supported by evidence in studies showing that high frequency exemplars are more likely to suffer retrieval-induced forgetting than low frequency exemplars (Anderson et al., 1994; see also Bäuml & Samenieh, 2010; Little, Storm, & Bjork, 2011; Shivde & Anderson, 2001; Storm, Bjork, & Bjork, 2007).

Instead of varying competitor strength by leveraging the pre-existing typicality of the materials, Jakab and Raaijmakers (2009) varied competitor strength episodically. Specifically, they manipulated competition either by varying input serial order (earlier items should have higher strength and thus be more competitive) or by varying number of encoding trials (Rp- items were presented once or twice). These methods are preferable to varying competition based on category norms because competitor strength is manipulated experimentally. Contrary to the prediction arising from competition dependence, in which a larger retrieval-induced forgetting effect should be observed for stronger than weaker competitors, Jakab and Raaijmakers reported no difference. Although it is reasonable to argue that these results are inconsistent with the inhibition account, it remains possible that that the retrieval-induced forgetting effect observed among the low-strength competitors was due to output interference instead of inhibition, because Jakab and Raaijmakers did not control output order in their category cued recall final test (for a detailed discussion, see Anderson, 2003; Murayama et al., 2014). We address this issue in more detail in our Introduction to Experiment 2.

## Why is competition dependence important?

Among the four major tenets in Anderson's inhibition theory (2003), we believe that competition dependence is the most important, because resolving competition is at the very root of the concept of inhibition. In a thoughtful consideration of the retrieval-induced forgetting literature, Verde (2013) pointed out that cue independence, strength independence, and retrieval dependence may not differentiate inhibition theory from many mathematical models of interference theories (Malmberg & Shiffrin, 2005), as the latter are capable of accounting for findings that have been used to support these three principles. Critically, Verde also declared that “interference [competition] dependence seems most able to differentiate between the [inhibition and interference] accounts.” But that “at present, the evidence does not strongly favor one account over the other” (p. 1444). Moreover, in a recent meta-analysis of the retrieval-induced forgetting literature, Murayama and colleagues (2014) noted that “given the importance of the [competition]-dependence property… it is surprising that there have not been more studies designed to test it” (p. 19).

Aside from the aforementioned studies (Anderson et al., 1994; Jakab & Raaijmakers, 2009) that were designed specifically to test the competition dependence assumption, several studies have provided data that can inform competition dependence, although most of these studies used manipulations that conflate two or more of the key principles of Anderson’s inhibition theory. For example, one method to examine competition dependence is to compare strengthening of the Rp+ items by retrieval practice or by restudying (Ciranni & Shimamura, 1999; Gómez-Ariza, Fernandez, & Bajo, 2012; Hulbert et al., 2012; Jonker et al., 2013; Staudigl, Hanslmayr, & Bäuml, 2010; Verde, 2013). The logic is that strengthening Rp+ items by study repetitions should not produce retrieval-induced forgetting because Rp- items would not compete, whereas strengthening based on retrieval practice should produce retrieval-induced forgetting. One downside of this methodology is that it conflates competition dependence with retrieval dependence.

Another method that has been used to test the competition dependence assumption is to compare exemplar retrieval practice with category retrieval practice. In category retrieval practice, subjects are given the exemplar and asked to recall the studied category name (e.g., Fr_ - Lemon). The idea is that the Rp- exemplars would not compete for retrieval when one attempts to recall a category name. Some researchers have found that category retrieval practice does not produce a retrieval-induced forgetting effect, even though it increased accessibility of the Rp+ items – essentially through restudying. This finding has been provided as evidence for the competition dependence assumption of inhibition theory (Anderson, Bjork, & Bjork, 2000; Grundgeiger, 2013; Hanslmayr, Staudigl, Aslan, & Bäuml, 2010). However, one problem with comparing exemplar retrieval practice with category retrieval practice is that it can conflate strength independence with competition dependence, as the category recall task is much easier and therefore less likely to strengthen the association between the Rp+ items and their category name (Jakab & Raaijmakers, 2009; Verde, 2013). In fact, even when care is taken to increase the difficulty of noncompetitive retrieval practice, the two methods still include very different task demands. In particular, the demand for retrieval itself is likely diminished in category retrieval practice, where it would be quite easy to guess the category under which an item belongs (e.g., Fr_ -Orange). Therefore, one could argue that category practice fails to produce retrieval-induced forgetting because its demand on retrieval, rather than competition resolution, is minimal. When interpreted this way, comparing competitive and noncompetitive retrieval practice conflates competition dependence and retrieval dependence.

In the present study, we introduce a paradigm specifically designed to address competition dependence that would have minimal influence on retrieval dependence and strength independence, thus providing the most direct test of competition dependence to date.

## The Interpolated Testing Paradigm

Here we introduce a new paradigm to manipulate competition during retrieval practice. To date, the typical retrieval-induced forgetting paradigm consists of three stages: a study phase during which all category-exemplars are learned, a retrieval practice phase during which all Rp+ exemplars are practiced, and a final test phase. In the present paradigm, instead of keeping the study phase and retrieval phase separate, we interspersed study and retrieval practice in four blocks. Specifically, in study block 1, participants studied one-quarter of the category-exemplar pairs. This was followed immediately by retrieval practice block 1, during which participants practiced retrieval on some of the studied items. This study+practice procedure was then repeated three more times, with a different set of materials for each study+practice block. We manipulated retrieval competition by varying whether the Rp+ items were practiced *before or after* participants had studied their Rp- counterparts. If the Rp+ items were practiced *before* the Rp- items were studied, the latter could not compete for retrieval and thus should not be suppressed. However, if the Rp+ items were tested *after* the Rp- items were studied, which is the case in virtually all existing retrieval-induced forgetting studies, then the Rp- items should compete for retrieval and hence be suppressed.

Using the four-block interpolating testing paradigm, we were able to manipulate whether retrieval practice of the Rp+ targets occurred before or after the Rp- competitors were studied. In the first two blocks of the *High-Competition* condition, participants studied Rp-, Nrp-, and filler items and then practiced retrieval on the filler items. In the last two blocks, participants studied Rp+, Nrp+, and filler items, and then they practiced retrieval on the Rp+ items. In the first two blocks of the *Low-Competition* condition, participants studied Rp+, Nrp+, and filler items and then practiced retrieval on the Rp+ items. In the last two blocks, participants studied Rp-, Nrp-, and filler items, and then they practiced retrieval on the filler items. Nrp items, of course, were never practiced. After a distractor-filled delay, participants completed the final test. A graphical depiction of the overall design is shown in Figure 1. Put simply, in the High-Competition condition, participants practiced retrieval of the Rp+ items after they had studied the Rp- competitors; in the Low-Competition condition, participants practiced retrieval of the Rp+ items before the corresponding Rp- items were studied.

There are three key advantages to this paradigm. First, we were able to vary competition without altering the method used to strengthen the Rp+ targets (so we did not conflate competition dependence with retrieval dependence). Second, we manipulated competition experimentally. Third, there was no subjectively discernible difference between the High- and Low-Competition conditions from the participants' perspective, which should in turn minimize the likelihood of strategy changes during the practice phase (e.g., participants may be particularly likely to engage in guessing rather than retrieval during category retrieval practice). This paradigm thus allowed us to test competition dependence without conflating it with strength independence (because all Rp+ items were studied and practiced the same number of times) and retrieval dependence (because all Rp+ items were strengthened by retrieval practice).

The core idea of the present paradigm rests on the assumption that nonstudied items would pose virtually no competition to the target, whereas items that were studied once would have gained substantial strength in episodic memory and therefore be more competitive.

Although a few studies have shown that nonstudied items can sometimes compete for target retrieval, such competition is likely restricted to items that are extremely accessible in semantic memory (Campbell & Phenix, 2009; Campbell & Thompson, 2012; Carter, 2004; Johnson & Anderson, 2004; Norman, Newman, & Detre, 2007). Regardless, it remains true that nonstudied items should be far less likely to compete for retrieval than studied items.[2]

## The Present Experiments

We conducted four experiments to examine whether or not retrieval-induced forgetting is driven to resolve competition among retrieval candidates. The four experiments used the same four-block, intervening retrieval practice design, but with tweaks to the final test to answer specific questions.

We sought to address two questions in Experiment 1. First, can reliable retrieval-induced forgetting be produced with the interpolated testing procedure using the present materials? To test this possibility, we included the traditional three-phase, *Cumulative Practice* procedure as a comparison condition. Second, and more importantly, is retrieval-induced forgetting affected by the level of competition from the Rp- items? If retrieval-induced forgetting is competition dependent, then it should be observed in the High-, but not the Low-,

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[2] In one experiment, Camp, Pecher, and Schmidt (2007) reported that nonstudied items could demonstrate retrieval-induced forgetting at a level similar to studied items. At first glance, this result suggests that nonstudied items may compete for retrieval as much as studied items. But closer examination of their data suggests that this is not the case, as the retrieval-induced forgetting effect for nonstudied items only occurred when the final test was likely contaminated by covert retrieval of the practiced Rp+ items. In fact, Camp and colleagues stated that “inhibition did not cause forgetting of unstudied items.” (p. 956)

Competition condition. In Experiment 1, the final test was administered using category-plus-stem cued recall so that we could control output order. Specifically, participants were always tested on the Rp- items before the Rp+ items for each category. This was done to eliminate output interference as a potential explanation for retrieval-induced forgetting. In Experiment 2, we used category cued recall during the final test, which involved asking participants to recall all studied exemplars based on a supplied category name. In this test, participants were free to output items within a category in any order. We conducted this experiment specifically to examine whether competition dependent retrieval-induced forgetting can be masked by factors such as output interference (Jakab & Raaijmakers, 2009; Storm & Levy, 2012; Williams & Zacks, 2001). Experiment 3 was a partial replication of Experiment 2, and it included only the High- and Low-Competition conditions. In Experiment 4, we tested participants' memory during the final test with recognition.

## Experiment 1

### Method

**Design.** Experiment 1 used a 3 (Retrieval practice condition: High-Competition, Low-Competition, Cumulative) X 3 (Item type: Rp+, Rp-, Nrp) mixed design. Retrieval practice condition was manipulated between-subjects and item type was manipulated within-subjects. As described previously and depicted in Figure 1, we varied competition during retrieval practice by manipulating whether participants had studied the Rp- items before (High-Competition) or after (Low-Competition) they practiced retrieval on the Rp+ items of the same category. Filler items were included so that a retrieval practice phase followed every study block (e.g., see blocks 1 and 2 in the High-Competition condition and blocks 3 and 4 in the Low-Competition condition in Figure 1). In the Cumulative Practice condition (i.e., traditional retrieval-induced forgetting procedure), participants studied all Rp+, Rp-, Nrp, and filler items during a single study block; they were then tested on the Rp+ items during a retrieval practice block before completing the final test. This condition was included to ensure that reliable retrieval-induced forgetting could be observed with the present materials - because it was possible that interpolating retrieval practice with studying would eliminate retrieval-induced forgetting altogether. We consider this logic in more detail during the General Discussion.

**Participants**. Ninety-six Iowa State University students participated in return for research credit, with 32 participants in each between-subjects condition.

**Materials and Procedure.** Participants studied 72 category-exemplar pairs, of which 48 were target pairs and 24 were filler pairs. The target pairs were taken from Experiment 3 of Anderson et al. (1994), which were divided equally among eight categories and had an average category frequency of .24 (*SD* = .20, Van Overschelde, Rawson, & Dunlosky, 2004). Filler pairs were spread across eight nontarget categories, and they had an average frequency of .25 (*SD* = .19). The complete set of materials appears in the Appendix.

Presentation order for the High- and Low-Competition condition was determined as follows. The eight target categories were randomly divided into two sets (of four), and the six items within each category were randomly divided into two sets (of three). Items in the first four categories were presented in blocks 1 and 3, and items in the remaining four categories were presented in blocks 2 and 4. For example, Profession - Farmer may appear in block 1 and Profession - Dentist may appear in block 3, whereas Fruit - Lemon may appear in block 2 and Fruit - Pineapple may appear in block 4. This was done so that the Rp- and Rp+ items from the same category could appear either in the first half or the second half of the learning phase, respectively. The same presentation order was applied to items in the Nrp categories as well, such that input order was the same regardless of whether an item had received retrieval practice. For example, Drink - Whiskey may appear in block 1 and Drink - Gin may appear in block 3. In the High-Competition condition, the Rp- items appeared in the first two blocks and Rp+ items appeared in the last two blocks, whereas the reverse was true in the Low-Competition condition. In the High- and Low-Competition conditions, participants studied six Rp exemplars (Rp+ or Rp-, depending on the block), six Nrp exemplars, and six filler exemplars during each block. In the Cumulative Practice condition, the Rp+, Rp-, Nrp, and filler items were randomly intermixed and presented sequentially.

In the learning phase, participants studied and practiced retrieval on the category-exemplar pairs. During each study trial, a category-exemplar pair was presented for 5 s. Throughout the experiment, a 500 ms interstimulus interval separated the presentation of all stimuli. During retrieval practice, participants were shown the category name and a two-letter stem of the exemplar. Participants had 5 s to type in the entire word of the exemplar. Each exemplar received retrieval practice three times. In the High- and Low-Competition conditions, each practice block contained three rounds of six unique test trials each (for a total of 18 trials). The six unique test trials appeared sequentially in a random order, except that items from the same categories did not appear on adjacent trials. Each round of the retrieval practice trials had a different random order. The same retrieval practice procedure occurred for participants in the Cumulative Practice condition, except that they performed all retrieval practice trials in a single phase.

Following the study and retrieval practice phase, participants played the videogame Tetris for 10 min as a distractor task. Afterwards, participants completed the final test. Here, participants were shown the category name and the first letter of the target exemplar (e.g., Weather – B____), and they had 7 s to type in their response. All exemplars in the same category were presented consecutively and in a random order, but the Rp- exemplars were always tested before the Rp+ exemplars.

To ensure that output order was taken into account when comparing items in the practiced categories (i.e., Rp+ and Rp-) with their nonpracticed counterparts (i.e., Nrp), the Nrp items that appeared in the same study blocks as the Rp- items were tested first during the final test—these items are designated *Nrp-* hereafter. This procedure thus ensures that the Rp- and Nrp- items had, on average, the same input and output order. Similarly, Nrp items that had the same average input and output positions as the Rp+ items are designated *Nrp+*.

The filler pairs were tested at the end of the test phase—after all target (Rp+, Rp-, and Nrp) pairs were presented.

**Predictions Based on Input/Output Order**

Because we manipulated competition by varying input and output orders, it is important to clarify these differences and how they might affect recall performance. The predictions regarding performance on the different item types are depicted in Table 1, where predicted performance are indicated by "+" and "-" signs. The "+" signs indicate higher predicted recall probability and the "-" signs indicate lower predicted recall probability. We used four general rules to guide our predictions. First, items studied earlier should benefit from primacy and reduced proactive interference relative to items studied later. We made this prediction based on the voluminous research that observed prominent primacy effects in long-term memory (Craik, 1970; Lockhart, 1975; Roediger & Crowder, 1976). Second, items with an earlier output order should show superior performance relative to items with a later output order, because the former would not suffer from output interference. Third, retrieval practice would greatly strengthen the

Rp+ items. Fourth, as per the inhibition account, retrieval practice would weaken the Rp- items, but only in the High-Competition condition. We readily acknowledge that predictions based on these four principles are rough estimates and they do not produce predictions regarding the exact magnitude of the effects.

To draw a concrete example, in the High-Competition condition, Nrp- items were studied earlier than the Nrp+ items. Thus, we predicted an input order advantage for the Nrp- items. Moreover, because Nrp- items were tested before their Nrp+ counterparts, we predicted an output order advantage for the Nrp- items as well. Therefore, we expected that Nrp- items would demonstrate superior performance to their Nrp+ counterparts due to the combined benefits of input and output orders. In the Low-Competition condition, however, the output order advantage of the Nrp- items was counteracted by the input order advantage of the Nrp+ items, so we expected no difference in recall probabilities between the Nrp- and Nrp+ items here (see Table 1).

Because we held input and output orders constant between the Nrp and Rp items *within conditions*, the predictions for the Nrp items also applied to the Rp items—except that the Rp items were subject to the combined influence of input/output order and retrieval practice. For example, as can be seen in the top half of Table 1, Rp- items were predicted to show poorer performance than Nrp- items in the High-Competition condition. If such a pattern were to occur, the difference cannot be attributed to input/output order effects, because these factors were equated across the two item types. Instead, any difference in performance between the Rp- and Nrp- items can only be attributed to retrieval practice.

**Results and Discussion**

Only results for the target items are reported.[3] Alpha level was set at .05. Partial eta squared ($\eta_p^2$) indicates effect size for analyses of variance (ANOVA) and Cohen's *d* indicates effect size for t-tests. All pairwise comparisons were planned and theoretically driven.

**Retrieval Practice Results.** There was a main effect of retrieval practice condition on initial test performance, $F(2, 93) = 6.46$, $p < .01$, $\eta_p^2 = .12$. As expected, Low-Competition practice produced the best performance ($M = .92$), followed by High-Competition practice ($M = .86$) and then Cumulative practice ($M = .82$). These data are not surprising, because retrieval practice of the Rp+ items occurred before their Rp- competitors were studied in the Low-Competition condition (which was reversed in the High-Competition condition), and because each practice block in the High- and Low-Competition conditions dealt with fewer studied items and a shorter retention interval (where each study block included 18 word pairs and lasted 99 s) than the Cumulative Practice condition (where the study block included all 72 pairs and lasted 360 s).

**Final Test Results.** Most important for present purposes, retrieval-induced forgetting was observed in the High-Competition condition ($M_{Rp-} = .56$ vs. $M_{Nrp-} = .64$), $t(31) = 2.24$, $p = .03$, $d = .41$, and the Cumulative Practice condition ($M_{Rp-} = .48$ vs. $M_{Nrp-} = .58$), $t(31) = 2.79$, $p < .01$, $d = .59$, but not in the Low-Competition condition ($M_{Rp-} = .55$ vs. $M_{Nrp-} = .53$), $t(31) = -.51$, $p = .61$, $d = .10$. There was a marginally significant interaction between Competition (High vs.

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[3] For the purpose of full disclosure, the filler items that received retrieval practice were recalled more often during the final test than those that did not, which was to be expected. Critically, however, the filler categories did not have any Rp- items, as they were introduced for the sole purpose of providing retrieval practice during the study blocks that included the Rp- items.

Low) and item type (Rp- vs. Nrp-), $F(1, 62) = 3.48$, $p = .07$, $\eta_p^2 = .05$. The results for these comparisons are displayed in the top panel of Figure 2. Moreover, a robust testing effect was observed for all three conditions, all $t$s > 8.08, $p$s < .01, $d$ > 1.74. These results are shown in the bottom panel of Figure 2.

Comparisons between the Nrp- and Nrp+ items revealed results consistent with our predictions (see Table 1). Specifically, the Nrp- items were recalled more frequently than the Nrp+ items in the High-Competition condition, $t(31) = 5.08$, $p < .01$, $d = .85$, but not in the Low-Competition condition, $t(31) = -.33$, $p = .74$, $d = .07$. Because the Nrp- items were recalled more frequently than the Nrp+ items in the High-Competition condition, one might be tempted to suggest that the retrieval-induced forgetting effect here was caused by a baserate difference rather than a genuine decline in performance for the Rp- items following competitive retrieval practice. This concern is unwarranted. As discussed previously and shown in Table 1, one can attribute superior recall of the Nrp- items (relative to Nrp+) in the High-Competition to its beneficial input/output order. Critically, because Rp- items had the same input/output order as their Nrp- counterparts, their recall performance should be the same, so any difference in performance between the Rp- and the Nrp- items must be due to the influence of retrieval practice. Here we interpreted the lower performance of the Rp- items (relative to the Nrp- items) in the High-Competition condition as evidence of retrieval inhibition.

The results in Experiment 1 are consistent with an inhibition account of retrieval-induced forgetting but are inconsistent with an interference account. However, these results clearly differ from those observed by Jakab and Raaijmakers (2009). As we have discussed in the Introduction, Jakab and Raaijmakers might have obtained equivalent retrieval-induced forgetting regardless of competitor strength because they used category cued recall as their final test, which did not allow one to control output order. When participants are free to output items within a category in any order, they are likely to recall the stronger Rp+ items before the weaker Rp- items, and output interference from the Rp+ items can then impair retrieval of the Rp- items (Bäuml, 1997). Thus, whether competition dependent retrieval-induced forgetting occurs may depend on the nature of the final recall test. Specifically, tests where participants are likely to output the Rp+ items before the Rp- items, such as category cued recall, may not show competition dependent retrieval-induced forgetting.

## Experiment 2

In this experiment, we sought to examine whether category cued recall is sensitive to the competition dependent retrieval-induced forgetting effect found in Experiment 1.

### Method

**Participants.** A total of 96 subjects participated in this experiment for research credits, with 32 participants in each between-subjects condition.

**Materials and Procedure.** The procedure was the same as Experiment 1 with two exceptions. First, the final test was category cued recall. On each test trial, a studied category name was presented (e.g., Fruit) and participants had 30 s to type in the exemplars (e.g., Lemon, Banana) studied under that category. The order of the categories was randomized. Second, participants completed the automatic Operation Span (OSPAN) working memory task (Unsworth, Heitz, Schrock, & Engle, 2005) in addition to playing Tetris during the retention interval, which lasted 20 min. We included the OSPAN task to examine whether retrieval-induced forgetting was related to working memory capacity (Aslan & Bäuml, 2011; but see Bell, 2005). We found no relation between OSPAN scores and the magnitude of retrieval-induced forgetting (Rp- recall probability minus Nrp recall probability), $r(96) = -.09$, $p = .40$, so this will not be discussed further.

Because we were unable to control output order in category cued recall, the designation of Nrp+ and Nrp- items were based only on their input order. Specifically, Nrp+ items were studied in the same blocks as the corresponding Rp+ items, and the Nrp- items were studied in the same blocks as the Rp- items. Moreover, the Nrp+ and Nrp- distinction applied only to the High- and Low-Competition conditions, but not to the Cumulative Practice condition, where the Nrp, Rp-, Rp+, and filler items were randomly intermixed during the study phase.

## Results and Discussion

**Retrieval Practice Results.** Similar to Experiment 1, retrieval practice performance was very high, with the Low-Competition condition producing numerically the best performance ($M$ = .90), followed by the High-Competition condition ($M$ = .87), and then the Cumulative Practice condition ($M$ = .84), $F(2, 93) = 2.60$, $p = .08$, $\eta_p^2 = .05$.

**Final Test Results.** The key finding of this experiment is that, unlike in Experiment 1, significant retrieval-induced forgetting was observed in the Low-Competition condition ($M_{\text{Rp-}}$ = .29 vs. $M_{\text{Nrp-}}$ = .37), $t(31) = 2.25$, $p = .03$, $d = .47$, in addition to the High-Competition condition ($M_{\text{Rp-}}$ = .32 vs. $M_{\text{Nrp-}}$ = .43), $t(31) = 3.78$, $p < .01$, $d = .62$, $d = .47$, and the Cumulative Practice condition ($M_{\text{Rp-}}$ = .28 vs. $M_{\text{Nrp-}}$ = .40), $t(31) = 4.94$, $p < .01$, $d = .80$ (see the top panel of Figure 3). Moreover, the 2 (High-Competition vs. Low-Competition) X 2 (Rp- vs. Nrp-) interaction was not significant, $F(1, 62) = .39$, $p = .53$, $\eta_p^2 = .01$. Similar to Experiment 1, all three conditions demonstrated a significant testing effect as well, all $t$s > 6.99, $p$s < .01, $d$s > 1.46 (see the bottom panel of Figure 3).

Because participants were free to output items in any order in the category cued recall test, we examined whether Rp- and Rp+ items had different output orders in the High- and Low-

Competition conditions based on the procedure outlined by Bäuml and Aslan (2006). We computed an output index for the Rp- and Rp+ items, respectively, by dividing the average output positions of each item type by the total output positions of all recalled items within a category. For example, if a participant recalled five items within a category and the Rp+ items occupied output positions 1, 2, and 5, whereas the Rp- items occupied positions 3 and 4, then the output index for the Rp+ items would be ((1 + 2 + 5)/3)/(1 + 2 + 3 + 4 + 5) = .18, and the average output index for the Rp- items would be ((3 + 4)/2)/(1 + 2 + 3 + 4 + 5)= .23. For this analysis, we included only trials for which participants had recalled at least one Rp- *and* one Rp+ item within a category.

As anticipated, the Rp- items ($M_{\text{High}}$ = .34, $M_{\text{Low}}$ = .40) were output later than the Rp+ items ($M_{\text{High}}$ = .28, $M_{\text{Low}}$ = .31) in both the High- and Low-Competition conditions, $t$s > 2.37, $p$s < .03, $d$s > .53. Therefore, unlike Experiment 1, where all Rp- items were tested before Rp+ items, the Rp- items in Experiment 2 were often recalled later than their Rp+ counterparts, and likely suffered from output interference from the Rp+ items that were recalled earlier. Critically, this output interference could produce a retrieval-induced forgetting effect (again, by either interference or test phase inhibition), regardless of whether or not inhibition had occurred during the retrieval practice phase, thereby making it difficult for one to ascertain the mechanism underlying the effect (Murayama et al., 2014).

The finding that Low-Competition retrieval practice produced retrieval-induced forgetting is clearly at odds with the finding in Experiment 1. When viewed in isolation, the present results might appear to lend support to the interference account (Jakab & Raaijmakers, 2009). But when these results are considered together with those from Experiment 1, they suggest that allowing participants to control output order likely contributed to the discrepant findings between Experiments 1 and 2.

## Experiment 3

Because the results differed substantially between Experiments 1 and 2, and theoretical support for either the inhibition or interference account hinges upon whether retrieval-induced forgetting can be observed in the Low-Competition condition when output order is controlled, we sought to replicate the results from Experiment 1.

### Method

**Participants.** Forty-eight participants were recruited for this experiment, with 23 in the High-Competition condition and 25 in the Low-Competition condition.

**Materials and Procedure.** Experiment 3 was identical to Experiment 1 except that it included only the High-Competition and Low-Competition conditions. We removed the Cumulative Practice condition because data from this condition do not differentiate the two theoretical accounts. Moreover, the results from Experiments 1 and 2 clearly showed that reliable retrieval-induced forgetting can be observed with the present materials — even when retrieval practice was administered in an interpolated manner. Experiment 3 thus served as a partial replication of Experiment 1.

### Results and Discussion

**Retrieval Practice Results.** Retrieval practice performance was generally very high, with participants in the Low-Competition condition ($M$ = .90) once again slightly, though not significantly, outperforming participants in the High-Competition condition ($M$ = .87), $t(46)$ = .70, $p$ = .49, $d$ = .20.

**Final Test Results.** The most important finding for this experiment is that a reliable retrieval-induced forgetting effect was found in the High-Competition condition ($M_{\text{Rp-}}$ = .57 vs. $M_{\text{Nrp-}}$ = .65), $t(22)$ = 2.20, $p$ = .04, $d$ = .48, but not in the Low-Competition condition ($M_{\text{Rp-}}$ = .58 vs. $M_{\text{Nrp+}}$ = .56), $t(24)$ = -.63, $p$ = .53, $d$ = .10. Moreover, there was a significant interaction between Competition (High vs. Low) and item type (Rp- vs. Nrp-), $F(1, 46)$ = 4.29, $p$ = .04, $\eta_p^2$ = .09. These results, which replicated those from Experiment 1, are displayed in the top panel of Figure 4. Retrieval practice also led to a testing effect, with higher performance for the Rp+ items relative to the Nrp+ items for both the High- and Low-Competition conditions, $t$s > 5.18, $p$s < .01, $d$s > 1.12. The results are shown in the bottom panel of Figure 4.

An examination of recall probabilities of the Nrp items again confirmed the predictions laid out in Table 1. Specifically, participants in the High-Competition condition recalled marginally more Nrp- items ($M$ = .65) than Nrp+ items ($M$ = .55), $t(22)$ = 1.74, $p$ = .10, $d$ = .59, whereas participants in the Low-Competition condition recalled the Nrp- ($M$ = .56) and Nrp+ ($M$ = .57) items at a similar rate, $t(24)$ = .32, $p$ = .76, $d$ = .07. Once again, as we pointed out in the Results and Discussion section of Experiment 1, any baserate differences between the Nrp- and Nrp+ items were by design, and these differences did not affect the validity of the retrieval-induced forgetting effect or the testing effect, because these effects were determined by comparing the Rp items with their corresponding Nrp items while holding input and output orders constant.

In sum, we replicated the findings from Experiment 1, whereby retrieval-induced forgetting was found following High-Competition retrieval practice, but not Low-Competition retrieval practice. This dissociation is consistent with the prediction based on the inhibition account.

**Experiment 4**

In Experiment 4, we used a free choice recognition test to assess memory performance. A debate has ensued over whether recognition testing is susceptible to interference effects in the same way of recall testing. In the context of retrieval-induced forgetting, several theorists have argued that recognition should be relatively interference-free, because the category cue is not presented during retrieval (Aslan & Bäuml, 2011; Veling & van Knippenberg, 2004). Thus, any retrieval-induced forgetting observed in recognition can only be attributed to inhibition (Anderson & Levy, 2007). However, empirical data (Criss, Malmberg, & Shiffrin, 2011) and simulation results from interference models (Malmberg & Shiffrin, 2005; Mensink & Raaijmakers, 1988) have demonstrated that, under some circumstances, recognition can be susceptible to interference effects, although none of these studies used the retrieval practice paradigm. Interference, in principle, can trigger retrieval-induced forgetting in recognition if the target copy cue causes spontaneous retrieval of the category name, which may then activate memory of the Rp+ items. This assumption was tested explicitly in a recent study by Grundgeiger (2013). In his Experiment 2A, Grundgeiger encouraged interference in recognition by first presenting the category cue for 2s before the to-be-recognized exemplar was presented. Despite using this procedure, he reported no retrieval-induced forgetting following a category retrieval practice task, which was consistent with the prediction from an inhibition account. Based on these results, Grundgeiger concluded that "at least in the context of [retrieval-induced forgetting], old/new recognition tests seem to be a reliable way of distinguishing between the different mechanisms as the cause of forgetting." (p. 417)

Our opinion is that it is risky to link any test format to specific cognitive operations, as any such assumptions are necessarily process-pure (see Jacoby, 1991). Therefore, we note here that we did not use recognition as the final test in Experiment 4 with the assumption that it is interference-free. Instead, we aimed to generalize our results from cued recall to recognition. Importantly, whether one believes that recognition is susceptible to interference effects is irrelevant in the present context, as it does not alter our theory-driven predictions.

Experiment 4 served an additional purpose. Specifically, we expected that the influence of input and output order to be greatly diminished in Experiment 4 relative to Experiments 1 and 3, as recognition is far less susceptible to these effects than is recall (Grundgeiger, 2013; Jones & Roediger, 1995). Thus, unlike the previous experiments, we may not observe any differences in performance between the Nrp+ and Nrp- items in the High-Competition condition. If a retrieval-induced forgetting effect is observed in this experiment, then it would further bolster our claim that the retrieval-induced forgetting effects from the previous experiments were not due to baserate differences in the Nrp items.

## Method

**Participants.** Forty-eight subjects participated in this experiment, with 24 in each between-subjects condition.

**Materials and Procedure.** The procedure in Experiment 4 was the same as in Experiment 1, except that the final test was free choice recognition. The recognition test contained 96 trials, half of which were targets and half were lures. The 48 lures were nonstudied exemplars from the studied categories, with six items per category. Therefore, half of the lure words were classified as *RpLures* and half were classified as *NrpLures*. RpLures were nonstudied exemplars from categories with which participants had performed retrieval practice, and NrpLures were from categories with which no retrieval practice took place. These lures had an average category frequency of .24 (*SD* = .22, Van Overschelde et al., 2004), which was virtually the same as that of the target items. The 96 trials were divided into six blocks of 16 trials each. Within each block of trials, one studied item and one lure were presented from each category, but the Rp- items were always tested before the Rp+ items. Similarly, the Nrp- items were always tested before the Nrp+ items. The recognition test was self-paced and the blocks of recognition trials were not visible to participants — that is, subjects completed the 96 recognition trials in a continuous fashion, with no breaks between each block.

## Results and Discussion

**Retrieval Practice Results.** Participants in the Low-Competition condition recalled most of the studied exemplars ($M$ = .92), as did participants in the High-Competition condition ($M$ = .86), $t(46) = 1.32$, $p = .19$, $d = .38$.

**Final Test Results.** Results for the final recognition test were scored as follows. Lure words were separated into a "-" set and a "+" set depending on their test order, with items tested in the first half of the recognition test, which matched the test order of the Nrp- and Rp- targets, designated as "-" lures, and items tested in the second half, which matched the test order of the Nrp+ and Rp+ targets, designated as "+" lures. We then computed an accuracy score for each target item type by subtracting the false alarm rate from its corresponding hit rate (e.g., $\text{Accuracy}_{\text{Rp+}} = \text{Hit}_{\text{Rp+}} - \text{FA}_{\text{Rp+Lures}}$). All statistical analyses were then conducted based on the accuracy scores, although the raw scores (i.e., the hit rates and false alarm rates) are displayed in Table 2 for reference.

Results from the recognition test are again consistent with the prediction based on the inhibition account. Specifically, a significant retrieval-induced forgetting effect was observed in the High-Competition condition ($M_{Rp-}$ = .47, $M_{Nrp-}$ = .54), $t(23) = 2.15$, $p = .04$, $d = .32$, but again not in the Low-Competition condition ($M_{Rp-}$ = .64, $M_{Nrp-}$ = .61), $t(23) = -.53$, $p = .60$, $d = .13$. However, due possibly to the smaller sample size of the present study, the interaction between Competition and item type was not significant, $F(1, 46) = 2.55$, $p = .12$, $\eta_p^2 = .05$. See Figure 5 for a depiction of these comparisons. A robust testing effect was also observed for both the High- and Low-Competition conditions, $t$s > 4.30, $p$s < .01, $d$s > .86. See the bottom panel of Figure 5 for the means.

In addition to examining the effects of retrieval practice competition on subsequent recognition performance, the present experiment also provided a test for whether the competition-dependent retrieval-induced forgetting effect was tied to differences in performance between the Nrp+ and Nrp- items (see Results of Experiments 1 and 3). Because recognition is typically far less susceptible to interference effects based on input and output order, we hypothesized that the performance difference driven by input/output order would be reduced in this experiment. This was indeed the case, whereas performance for the Nrp- items was consistently better than the Nrp+ items in the High-Competition condition in recall, this baseline difference was absent in recognition ($M_{Nrp-}$ = .54, $M_{Nrp+}$ = .52), $t(23) = .51$, $p = .62$, $d = .12$. Therefore, it is clear that competition during retrieval practice can produce retrieval-induced forgetting, even when no difference in baseline performance exists.

**Additional Analyses Based on Data from All Four Experiments**

Because the 2 (High-Competition vs. Low-Competition) X 2 (Rp- vs. Nrp) interaction was not significant in Experiment 4 and only marginally significant in Experiment 1, we attempted to increase power to detect this interaction by combining the data from Experiments 1, 3, and 4. We did not include Experiment 2 in this analysis because we had hypothesized, a priori, that its procedure was not conducive to observing competition-dependent retrieval-induced forgetting. This analysis showed a significant interaction between competition and item type, $F(1, 158) = 9.89$, $p = < 01$, $\eta_p^2 = .06$. When the data across the three experiments were combined, there was a significant retrieval-induced forgetting effect in the High-Competition condition ($M_{\text{Rp-}} = .53$, $M_{\text{Nrp-}} = .61$), $t(78) = 3.80$, $p < .01$, $d = .38$, but it was completely absent in the Low-Competition condition (and in the reversed direction), ($M_{\text{Rp-}} = .58$, $M_{\text{Nrp-}} = .56$), $t(80) = -.93$, $p = .35$, $d = -.11$.

To further examine whether increased strength of the Rp+ items contributed to retrieval-induced forgetting of the Rp- items by blocking their retrieval, we conducted a correlation analysis. Several researchers (Aslan & Bäuml, 2011; Murayama et al., 2014; Staudigl et al., 2010) have argued that if retrieval-induced forgetting occurs due to blocking, then the magnitude of the testing effect (i.e., superior recall of Rp+ items relative to recall of Nrp+ items) should be associated with the magnitude of retrieval-induced forgetting (i.e., inferior recall of the Rp- items relative to recall of the Nrp- items). The logic of this analysis is that greater strengthening of the Rp+ items via retrieval practice should increase the likelihood they will block retrieval of the Rp- items. We conducted this correlation analysis based on the data from Experiments 1, 3, and 4 separately for the Low-Competition and High-Competition conditions. Our results showed that the magnitude of the testing effect was not associated with the magnitude of retrieval-induced forgetting in both the Low-Competition, $r(81) = -.03$, $p = .78$, and High-Competition conditions, $r(79) = -.01$, $p = .95$. Lastly, we conducted the same correlation analysis for Experiment 2, where we expected associative blocking to play a larger role in the retrieval-induced forgetting effect observed. The correlation in the High-Competition condition was in the predicted direction (i.e., a greater testing effect was associated with a greater retrieval-induced forgetting effect) but was not significant, $r(32) = .22$, $p = .22$. Strikingly, however, despite the small sample size, a sizable correlation was found between the testing effect and retrieval-induced forgetting in the Low-Competition condition, $r(32) = .57$, $p < .01$. This correlation is consistent with the idea that the significant retrieval-induced forgetting effect in the Low-Competition condition in Experiment 2 was based on associative blocking rather than inhibition.

Extant findings for this type of correlation analysis favors the inhibition account, with several studies showing no correlation between testing effect and retrieval-induced forgetting (Aslan & Bäuml, 2011; Hulbert et al., 2012; for a review, see Murayama et al., 2014). Critics of this approach (Raaijmakers & Jakab, 2013) have rightfully argued that attempting to correlate two change scores (i.e., testing effect and retrieval-induced forgetting) may result in no correlation simply because change scores are unreliable. When viewed with this critique in mind, the significant correlation in Experiment 2 is even more telling. Moreover, given that this pattern was consistent with our prediction and the overall pattern in the literature (Murayama et al., 2014), we find it unlikely the correlation here is spurious.

## General Discussion

In four experiments, we manipulated the level of competition between the Rp+ and Rp- exemplars during retrieval practice and showed that retrieval-induced forgetting was observed only when the Rp- exemplars could compete during practice. In Experiment 1, retrieval-induced forgetting was observed in category-plus-stem cued recall following Cumulative or High-Competition retrieval practice, but it was absent following Low-Competition retrieval practice. In Experiment 2, using category cued recall, where participants determined output order, retrieval-induced forgetting was observed in all conditions, including the Low-Competition condition. We then replicated the finding of competition-dependent retrieval-induced forgetting in Experiment 3 and extended it to recognition in Experiment 4.

In these experiments, we manipulated competition by varying only the input order of the study items, thereby avoiding numerous methodological problems that can cloud interpretation of the results. In particular, we manipulated competition without altering 1) the practice method, 2) the associative strength between the category and exemplars, and 3) the item strength of the practiced and nonpracticed items. This paradigm thus allowed for a relatively pure investigation of competition dependence, which we believe is the most convincing distinction between inhibition and other accounts of retrieval-induced forgetting. We now discuss the implications of our results in relation to the major theories that have been proposed to explain retrieval-induced forgetting, including interference, inhibition, and the recently proposed context account (Jonker et al., 2013).

**The Interference Account**

If retrieval-induced forgetting is based on interference during the final test, it should be observed in both the High- and Low-Competition conditions. In our paradigm, the Rp+ exemplars were strengthened by the same method—retrieval practice—in both the High- and Low-Competition conditions, so these practiced exemplars should interfere with retrieval of the nonpracticed Rp- exemplars during the final test in both conditions. The complete lack of retrieval-induced forgetting following noncompetitive retrieval practice is difficult for interference theories to explain. Indeed, the particularly troublesome results may be those from Experiment 2, where retrieval-induced forgetting appeared to be unaffected by our competition manipulation. This result is similar to those reported by Jakab and Raaijmakers (2009), which were often cited as evidence against the inhibition account. Here we showed that this *competition-independent* effect is likely attributable to the use of category cued recall (also used by Jakab and Raaijmakers), where output interference can produce a retrieval-induced forgetting-like effect.

Can interference theory account for these findings? One possible argument is that Low-Competition practice strengthened the Rp+ items less than High-Competition practice. The logic is that successful retrieval of the target under high competition would require one to overcome interference, which may be particularly beneficial to subsequent memory (Carpenter & DeLosh, 2005). If this is the case, interference theory would predict less retrieval-induced forgetting following Low-Competition practice than High-Competition practice. This argument, however, fails to explain the complete absence of retrieval-induced forgetting in the Low-Competition conditions in Experiments 1, 3, and 4, where output interference was eliminated as a potential mechanism. Even if Low-Competition practice were to strengthen the Rp+ items to a less extent than High-Competition practice, it had undoubtedly increased accessibility of the Rp+ items (and so should produce retrieval-induced forgetting), as is evident by the robust testing effect observed in the Low-Competition condition across all experiments.

To further examine whether Low-Competition retrieval practice strengthened the Rp+ items to a smaller extent than High-Competition retrieval practice, we performed a 2(Competition: High- vs. Low-Competition) X 2 (Item type: Nrp+ vs. Rp+) mixed ANOVA based on the combined data across all four experiments. The results revealed no interaction between competition and item type, $F(1, 222) = .80$, $\eta_p^2 < .01$. Indeed, the Low-Competition condition produced a testing effect ($M = .29$, computed by subtracting recall probability of Nrp+ from Rp+) that was at least equal to that of the High-Competition condition ($M = .26$). Clearly, retrieval practice in the Low-Competition condition strengthened the practiced items to a similar extent as the High-Competition condition, so differential strengthening of the Rp+ items cannot effectively account for the absence of retrieval-induced forgetting in the Low-Competition condition.

**The Context Account**

In a recent paper, Jonker and MacLeod (2013) proposed a new theoretical account for retrieval-induced forgetting. Unlike interference theory and inhibition theory, this account relies on context change and context reinstatement to explain retrieval-induced forgetting (see also Verde, 2013). Specifically, participants form an encoding context when they study the category-exemplar pairs. When the task switches from encoding to retrieval practice, it triggers an internal context change. Then, when participants perform the final test, presentation of a nonpracticed (Nrp) category cue reinstates the study context, because the Nrp categories appear during only the study phase. This context reinstatement should benefit retrieval of the Nrp items. In contrast, practiced (Rp) categories are associated with both the study and retrieval practice contexts. Therefore, when a practiced category cue is presented during the final test, it could, in principle, reinstate either the study or retrieval practice context. But the retrieval practice context, instead of the study context, is likely to be reinstated because it is *more recent* and retrieval practice itself is *more elaborative.*[4] Because the Rp- items are *not presented* during

[4] We should add here that another possible reason that the practiced category cue would favor reinstatement of the retrieval practice context is that presentation of the cue during the final test would better match the perceptual form of its presentation during retrieval practice, where at least part of the target exemplar is omitted from presentation.

retrieval practice, reinstatement of this context would not benefit their recall. Therefore, according to this context account, retrieval-induced forgetting is the byproduct of enhanced recall performance of the Nrp items due to context reinstatement, rather than a decrement in recall of the Rp- items due to inhibition or interference. According to Jonker and MacLeod, retrieval-induced forgetting would occur only when two conditions are satisfied. First, a context change must happen between study and practice; second, the practice context, rather than the study context, must be reinstated when the Rp- items are tested.

Although the present experiments were not designed specifically to test the context account, we can nevertheless consider whether this new account is supported by our findings. At first glance, it is difficult to envision how the context account, as it is currently conceived, can explain the competition dependent effect observed in our experiments, given that virtually nothing separated the High- and Low-Competition conditions from a procedural (which can influence context change) perspective. As it currently stands, the context account is underspecified for one to make specific predictions about whether a practiced category cue would reinstate the study or retrieval practice context in the Low-Competition condition. A modified version of the context account, however, may be able to explain the elimination of the retrieval-induced forgetting effect in the Low-Competition condition.

According to the context account, unless steps are taken to purposefully reinstate the study context, the practiced category cue would reinstate the retrieval practice context because of two factors: First, the retrieval practice phase is *more recent*, and second, the retrieval practice phase is *more elaborative*. In the High-Competition condition, these two factors worked in concert to reinstate the retrieval practice context (see the top half of Figure 1). However, in the Low-Competition condition (see the bottom half of Figure 1), these factors worked in opposition.

Specifically, when a practiced category cue is presented during the final test, it should reinstate the study context if context reinstatement *favors recency*, because the Rp- items (and their associated category cue) were studied in blocks 3 and 4. This would lead one to predict no retrieval-induced forgetting in the Low-Competition condition. Alternatively, if context reinstatement *favors elaboration*, the cue should reinstate the retrieval practice context in blocks 1 and 2, and one would predict retrieval-induced forgetting in the Low-Competition condition. Lastly, if these forces *counteract* each other, then the study and retrieval practice contexts might be reinstated equally often, and one might predict a smaller, though perhaps still reliable, retrieval-induced forgetting effect in the Low-Competition condition relative to the High-Competition condition. Because no retrieval-induced forgetting was observed in the Low-Competition condition, one must assume that the category cue had reinstated the study context. Therefore, based on the present data, recency appears to take precedence in context reinstatement.

This explanation is, of course, post hoc. To be fair, the context account was developed on the grounds of the three-phase, traditional retrieval-induced forgetting paradigm, and it is not possible for Jonker and MacLeod (2013) to foresee the present, more complex multi-block design as it is applied to retrieval-induced forgetting. But as our consideration illustrates, the context account, with some additional assumptions, can provide a post hoc explanation for the present data. A proper test of this context account, however, must include a manipulation of context reinstatement. Based on Jonker and MacLeod's theory, retrieval-induced forgetting should not occur in the Low-Competition condition if the study context is reinstated, but it should occur if the retrieval practice context is reinstated. These predictions differ from those based on inhibition theory, which would lead one to predict no retrieval-induced forgetting following Low-Competition retrieval practice, no matter which context is reinstated. So it is possible to pit these accounts against each other in an empirical test. As is, the present data are consistent with both the inhibition account and a modified version of the context account.

We would be remiss not to note that many modern interference models include context as a parameter that can influence recall (Mensink & Raaijmakers, 1988). Therefore, it is conceivable that these models can also fit our finding provided that the context parameter was set such that the study context, rather than the retrieval practice context, was reinstated in the Low-Competition condition. Of course, similar to the context account, such an assumption is post hoc.

### The Importance of Competition Dependence to the Inhibition Account of Retrieval-Induced Forgetting

As our results clearly demonstrated, retrieval-induced forgetting is competition dependent. Competition dependence is a hallmark of the inhibition theory as competition resolution is theorized to be the very mechanism from which suppression arises (Anderson et al., 1994). Indeed, no matter how one views inhibition theory, competition dependence must remain its critical assumption, as it is at the very core of its theoretical construct. In contrast, the other three assumptions, namely cue independence, strength independence, and retrieval dependence, are less tied to the fundamental concepts underlying inhibition theory.

For example, cue independence stems from one version of the inhibition account that posits that inhibition acts at the item level, rather than at the association level (Anderson, 2003). According to this version of the account, the negative impact of inhibition should be revealed regardless of the way targets are cued. But the cue independence assumption has come under questions as some researchers have failed to report the effect (K. M. Butler, Williams, Zacks, &

Maki, 2001; Camp, Pecher, & Schmidt, 2005; Camp, Pecher, Schmidt, & Zeelenberg, 2009; Perfect et al., 2004). An alternative version of the inhibition account can emphasize the role that inhibition plays on the association between the cue and the target, and less so on the target itself (Murayama et al., 2014; Storm & Levy, 2012). Admittedly, adopting such a theoretical perspective may make inhibition theory more similar to interference theory, but the major distinction of *active weakening* of some memorial representation remains, and this is an idea unique to inhibition.

Overall, there is relatively strong empirical evidence for the strength independence assumption (Erdman & Chan, 2013; Storm & Nestojko, 2010), but a problem with strength independence is that more sophisticated, modern interference accounts are able to account for patterns consistent with strength independence (Verde, 2013). Perhaps more importantly, strength independence is unlikely to apply under all conditions. For example, performing retrieval practice on very strong, and thus highly recallable, targets may not lead to retrieval-induced forgetting (e.g., the exemplar Apple for the category Fruit, or the exemplar Blue for the category Color), as these very strong targets may negate any competition stemming from the nontargets (see also Anderson, 2003, p. 428). In this sense, the concept of strength independence is a corollary of competition dependence, because inhibition is driven by competitor interference rather than strengthening of the practiced items.

Although Anderson (2003) postulated retrieval dependence as a separate assumption from competition dependence, another interpretation is that retrieval dependence is founded on the assumption that inhibition is triggered to resolve competition, and competition from nontargets are most likely to occur when one attempts to retrieve. However, Verde (2013) has demonstrated that practice tasks that do not require retrieval (e.g., decide whether a target exemplar is a good representative of the category) can also impair subsequent recall of the competitors. Indeed, retrieval dependence, like cue independence, may not be a necessary assumption for the inhibition theory, as the core principle here is that suppression is triggered to resolve competition, rather than to resolve competition *during retrieval* per se.

Despite its wide application and general support (Storm & Levy, 2013), inhibition theory has encountered significant criticisms recently (Jonker et al., 2013; Raaijmakers & Jakab, 2013; Verde, 2012; 2013). These researchers argued that substantial empirical evidence has emerged that points toward a revision of the inhibition account proposed by Anderson and colleagues (but see Murayama et al., 2014; Storm & Levy, 2012). Our view is that it might be worthwhile to reconsider the relatively equal footing that researchers heretofore have given the four principles. As we have argued, we believe that competition dependence should be viewed with renewed significance, as this principle is driven by the underlying core assumption of inhibition — that inhibition arises to resolve competition in memory.

**Conclusion**

We believe that competition dependence is the most important and fundamental concept to the theory of inhibition, at least in its application to retrieval-induced forgetting. In four experiments, we have shown that retrieval practice of the targets only produced forgetting of the nonpracticed items if the latter interfered with target recall. These results favor the core principle of inhibition.

Table 1

*Predicted Effects of Input Order, Output Order, and Retrieval Practice on Final Test Performance*

| | | | Predicted Performance Based on | | | |
|---|---|---|---|---|---|---|
| Item Type | Input Order | Output Order | Input | Output | Retrieval Practice | **Net Effect** |
| High-Competition | | | | | | |
| Rp+ | Late | Late | – | – | + + + + + | + + + |
| Rp- | Early | Early | + | + | – | + |
| Nrp+ | Late | Late | – | – | | – – |
| Nrp- | Early | Early | + | + | | + + |
| Low-Competition | | | | | | |
| Rp+ | Early | Late | + | – | + + + + + | + + + + |
| Rp- | Late | Early | – | + | | / |
| Nrp+ | Early | Late | + | – | | / |
| Nrp- | Late | Early | – | + | | / |

*Note.* Predictions were derived from differences in input order, output order, and retrieval practice. A "+" sign indicates an advantage, a "–" sign indicates a disadvantage. Based on the inhibition theory, we hypothesized that retrieval practice would weaken recall for the Rp- items, but only in the High-Competition condition. The testing effect for the Rp+ items is hypothesized to be far more powerful than other factors, and would likely overwhelm differences in input and output order. The five plus signs associated with retrieval practice effect is admittedly arbitrary, although this estimate is based on the general idea that initial testing often produces very large benefits to memory performance relative to effects based on variations in input and output order. The key, however, is that the input and output orders were held constant when comparing performance between the appropriate item types within-subjects (e.g., comparing Rp- to Nrp- and comparing Rp+ to Nrp+).

Table 2

*Raw Probabilities of Hits and False Alarms as a Function of Competition and Item Type in Experiment 4*

| Item Type | Hit Rate for Targets | False Alarm Rate for Lures |
|---|---|---|
| High-Competition | | |
| Rp+ | 0.93 (.11) | 0.22 (.17) |
| Rp- | 0.65 (.22) | 0.18 (.16) |
| Nrp+ | 0.74 (.13) | 0.22 (.17) |
| Nrp- | 0.75 (.16) | 0.21 (.16) |
| Low-Competition | | |
| Rp+ | 0.95 (.08) | 0.12 (.09) |
| Rp- | 0.75 (.18) | 0.12 (.10) |
| Nrp+ | 0.71 (.14) | 0.18 (.14) |
| Nrp- | 0.74 (.19) | 0.13 (.09) |

*Note.* Standard deviations are presented in parentheses.

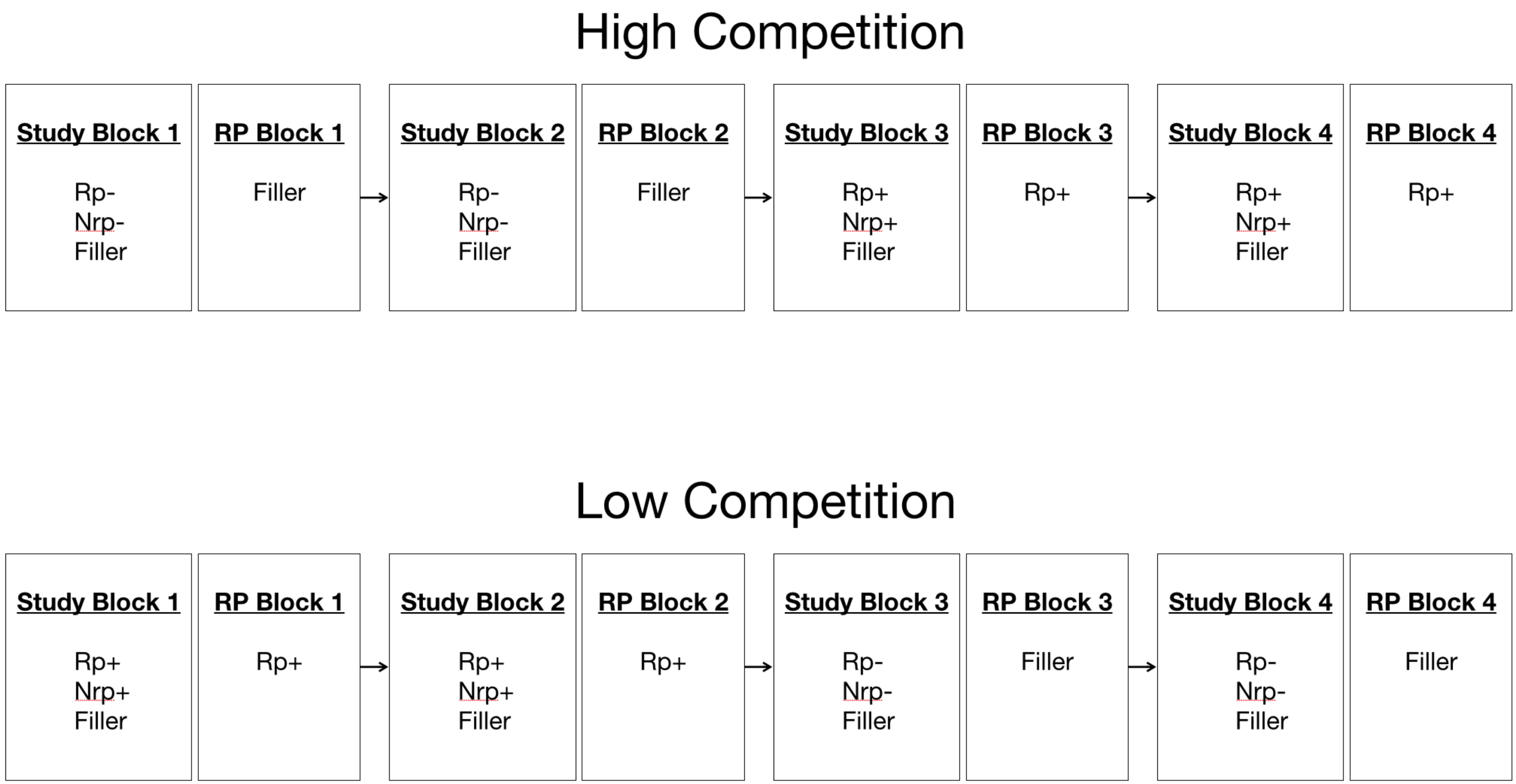


*Figure 1.* A graphical depiction of the learning phase in the High- and Low-Competition conditions in the four experiments.

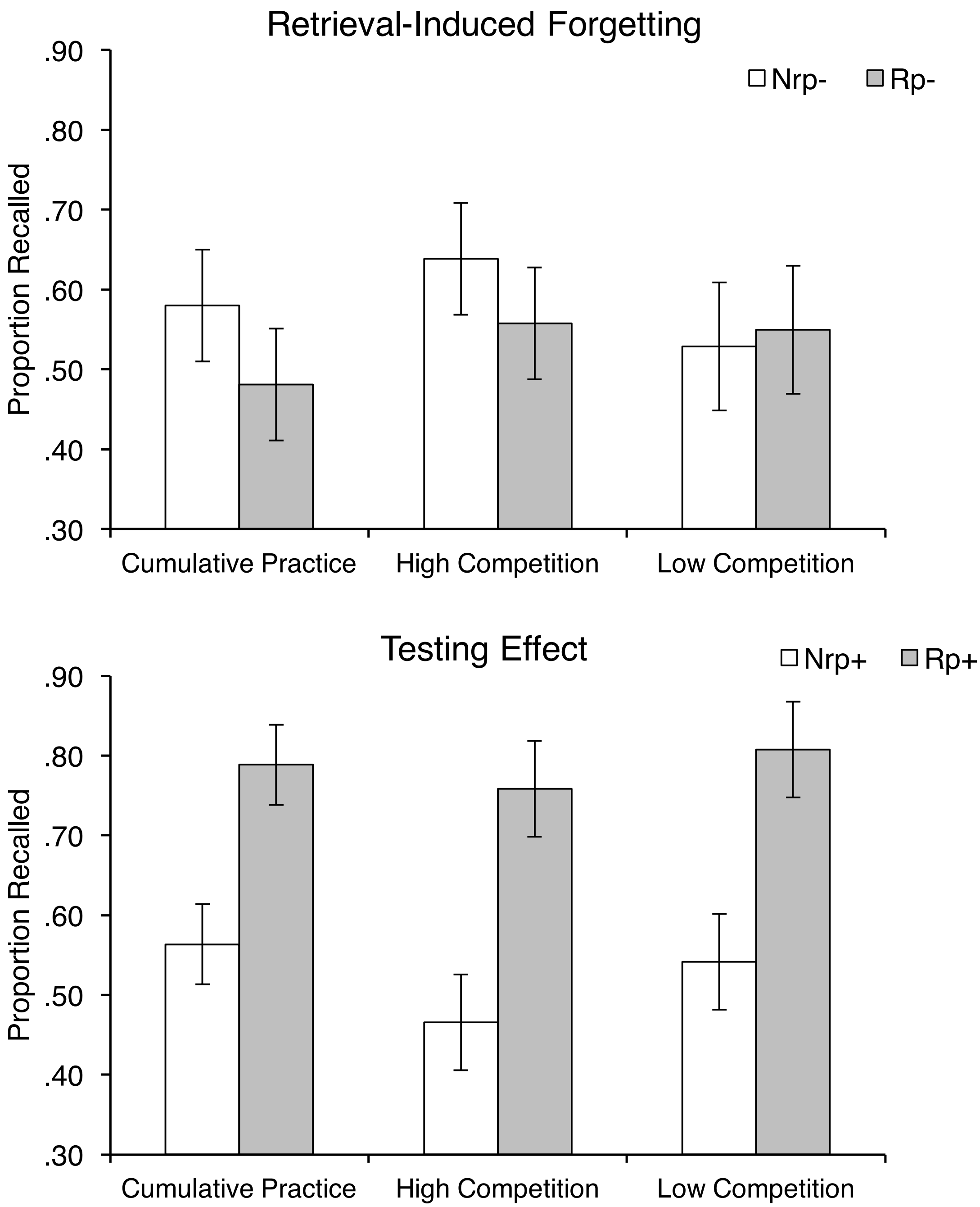


*Figure 2.* Recall performance on the final category and stem cued recall test in Experiment 1. Error bars are within-subjects .95 *CI*.

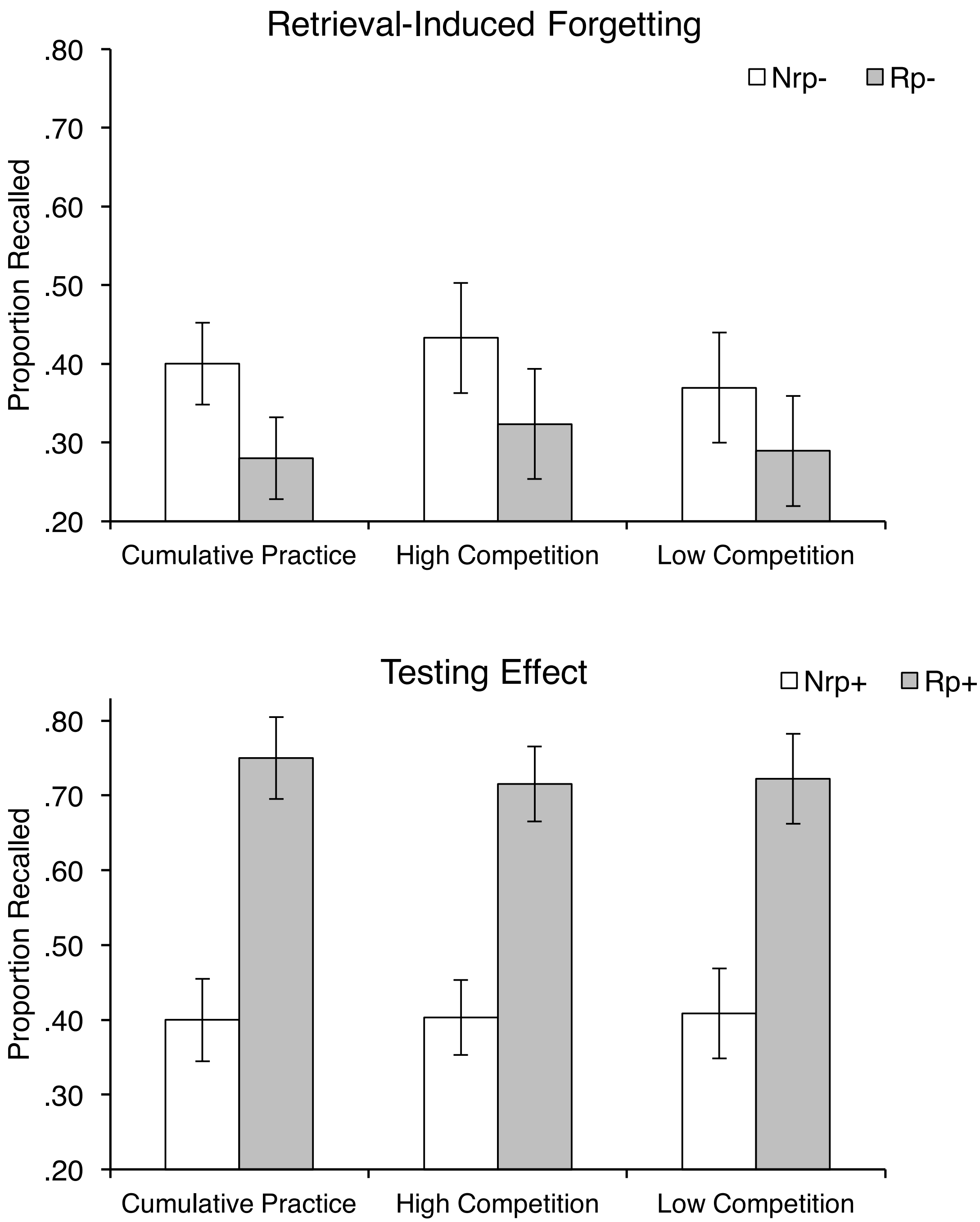


*Figure 3.* Recall performance on the final category cued recall test in Experiment 2. Error bars are within-subjects .95 *CI*. Note that the distinction between Nrp- and Nrp+ items did not exist in the Cumulative Practice condition. Identical values were used for Nrp- and Nrp+ items in this condition for the sole purpose of simplifying visual presentation of the results.

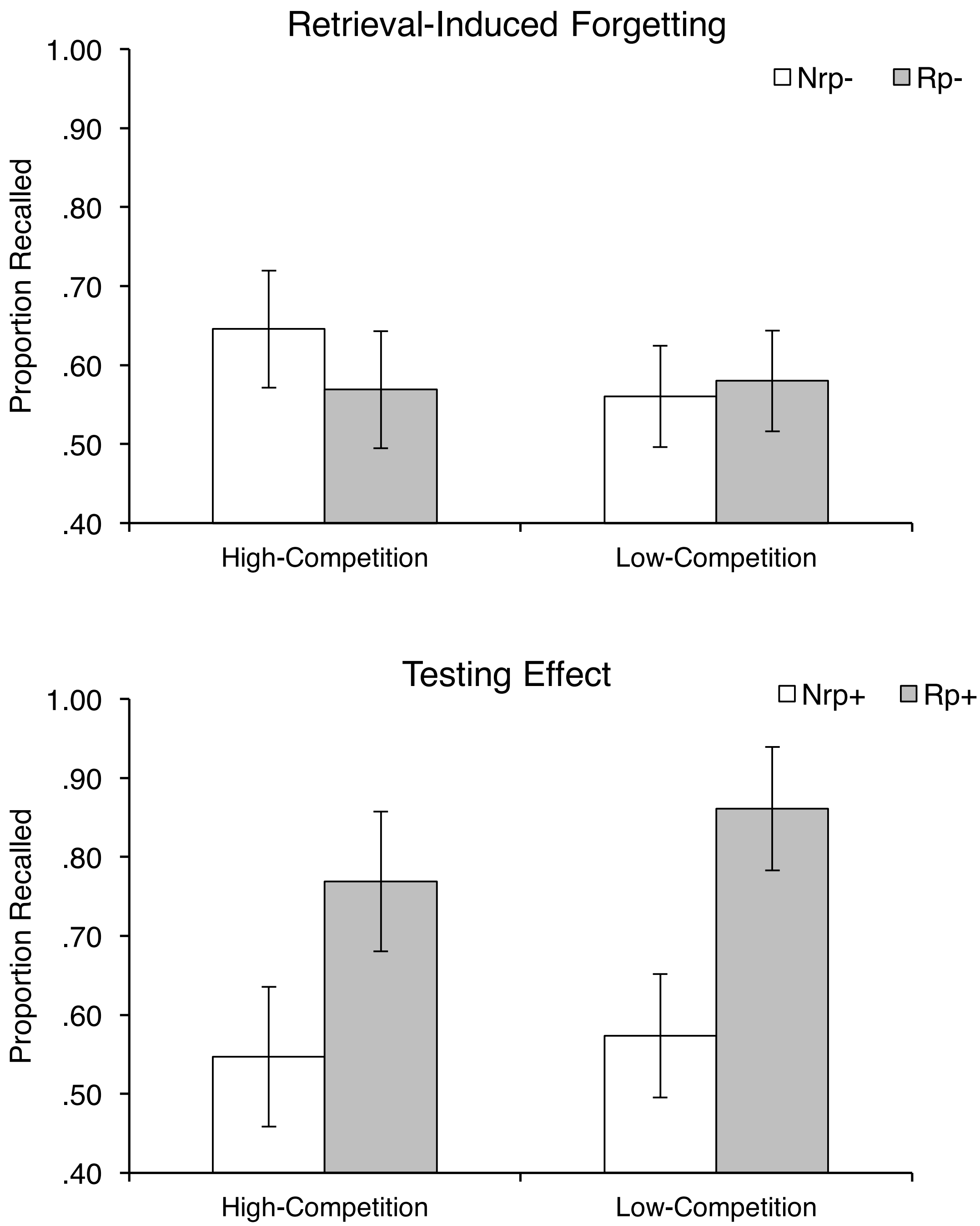


*Figure 4.* Recall performance on the final category and stem cued recall test in Experiment 3. Error bars are within-subjects .95 *CI*.

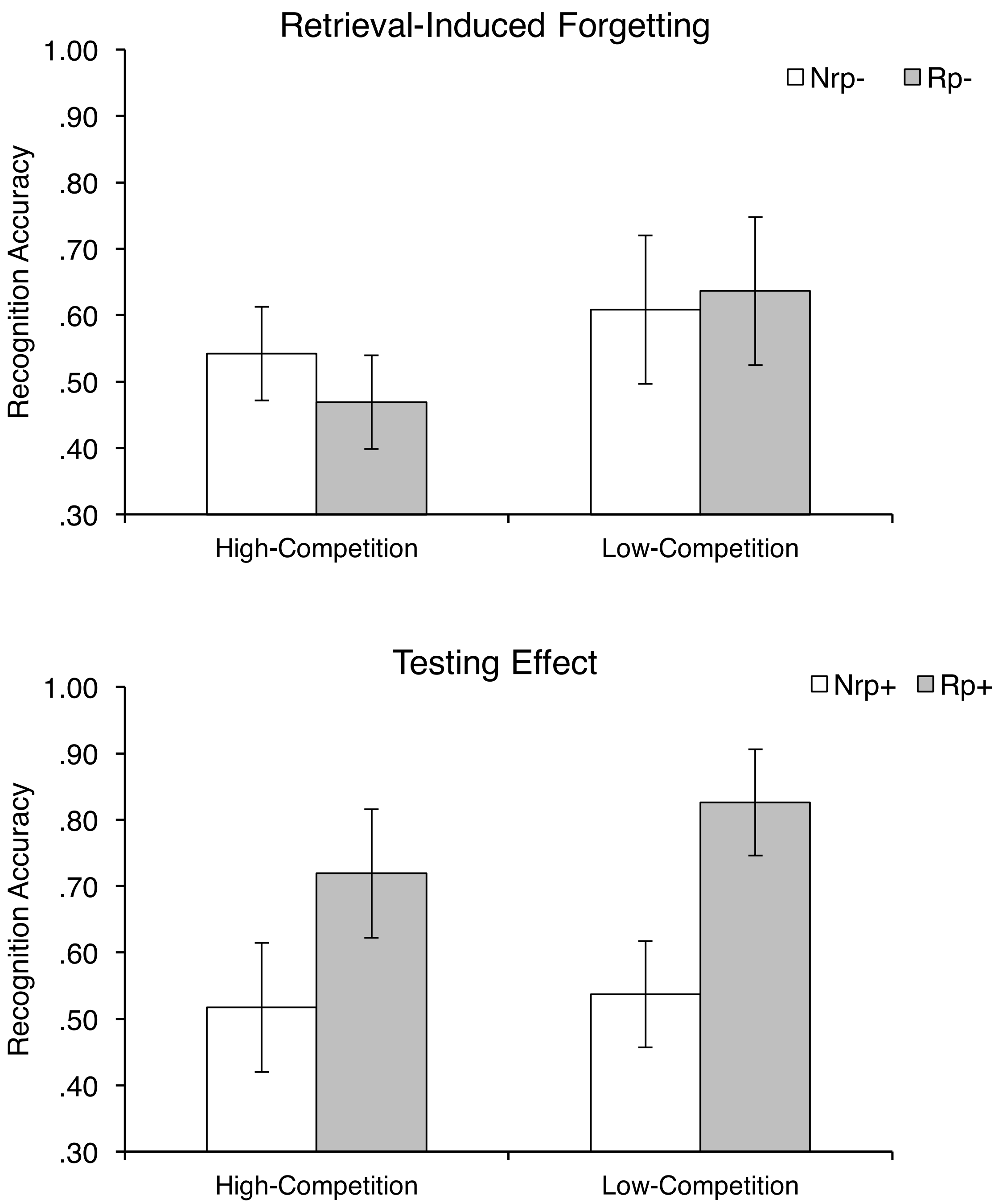


*Figure 5.* Performance on the final recognition test in Experiment 4. Error bars are within-subjects .95 *CI*.

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## Appendix A

Target Category and Exemplars used in Experiments 1 – 4

| Category | Exemplar | Van Overschelde et al. (2004) Frequency |
|---|---|---|
| Weapon | Pistol | 0.08 |
| | Tank | 0.04 |
| | Sword | 0.28 |
| | Club | 0.06 |
| | Rifle | 0.12 |
| | Bomb | 0.18 |
| Metal | Iron | 0.57 |
| | Nickel | 0.13 |
| | Gold | 0.53 |
| | Silver | 0.55 |
| | Aluminum | 0.43 |
| | Brass | 0.09 |
| Profession | Farmer | 0.06 |
| | Dentist | 0.12 |
| | Nurse | 0.25 |
| | Plumber | 0.03 |
| | Engineer | 0.1 |
| | Accountant | 0.13 |
| Fruit | Strawberry | 0.40 |
| | Lemon | 0.15 |
| | Orange | 0.86 |
| | Tomato | 0.23 |
| | Banana | 0.71 |
| | Pineapple | 0.26 |
| Insect | Hornet | 0.05 |
| | Fly | 0.61 |
| | Roach | 0.16 |
| | Beetle | 0.31 |
| | Mosquito | 0.33 |
| | Grasshopper | 0.20 |
| Fish | Guppy | 0.07 |
| | Bluegill | 0.04 |
| | Trout | 0.51 |
| | Herring | 0.11 |
| | Catfish | 0.27 |

| | | |
|---|---|---|
| | Flounder | 0.18 |
| Drink | Ale | 0.02 |
| | Rum | 0.43 |
| | Vodka | 0.62 |
| | Whiskey | 0.32 |
| | Bourbon | 0.05 |
| | Gin | 0.23 |
| Tree | Elm | 0.1 |
| | Redwood | 0.2 |
| | Dogwood | 0.18 |
| | Birch | 0.13 |
| | Hickory | 0.03 |
| | Spruce | 0.16 |

**Appendix B**

Foil Category and Exemplars used in Experiments 4

| Category | Exemplar | Van Overschelde et al. (2004) Frequency |
|---|---|---|
| Weapon | Bat | 0.22 |
| | Mace | 0.09 |
| | Axe | 0.08 |
| | Grenade | 0.08 |
| | Missile | 0.08 |
| | Hammer | 0.06 |
| Metal | Steel | 0.62 |
| | Copper | 0.53 |
| | Platinum | 0.17 |
| | Titanium | 0.17 |
| | Tin | 0.15 |
| | Bronze | 0.14 |
| Profession | Fireman | 0.14 |
| | Professor | 0.14 |
| | Secretary | 0.1 |
| | Manager | 0.09 |
| | Cook | 0.07 |
| | Banker | 0.05 |
| Fruit | Apple | 0.95 |
| | Grape | 0.52 |
| | Pear | 0.5 |
| | Peach | 0.4 |
| | Kiwi | 0.3 |
| | Watermelon | 0.24 |
| Insect | Ant | 0.57 |
| | Bee | 0.41 |
| | Ladybug | 0.27 |
| | Butterfly | 0.19 |
| | Wasp | 0.17 |
| | Moth | 0.15 |
| Fish | Salmon | 0.51 |
| | Bass | 0.33 |
| | Swordfish | 0.15 |
| | Carp | 0.1 |
| | Marlin | 0.05 |

| | | |
|---|---|---|
| | Mackerel | 0.02 |
| Drink | Beer | 0.87 |
| | Wine | 0.54 |
| | Tequila | 0.24 |
| | Champagne | 0.09 |
| | Scotch | 0.09 |
| | Brandy | 0.04 |
| Tree | Maple | 0.45 |
| | Aspen | 0.2 |
| | Cherry | 0.13 |
| | Palm | 0.1 |
| | Cedar | 0.09 |
| | Willow | 0.07 |

**Appendix C**

Filler Category and Exemplars used in Experiments 1 – 4

| Category | Exemplar | Van Overschelde et al. (2004) Frequency |
|---|---|---|
| Toy | Wagon | 0.02 |
| | Jacks | 0.03 |
| | Puzzle | 0.06 |
| Weather | Lightning | 0.21 |
| | Typhoon | 0.11 |
| | Blizzard | 0.18 |
| Spice | Oregano | 0.39 |
| | Mustard | 0.10 |
| | Nutmeg | 0.05 |
| Body | Nose | 0.53 |
| | Finger | 0.67 |
| | Ear | 0.49 |
| Bird | Crow | 0.24 |
| | Bluebird | 0.29 |
| | Parakeet | 0.12 |
| Flower | Orchid | 0.09 |
| | Lily | 0.3 |
| | Pansy | 0.11 |
| Clothing | Skirt | 0.61 |
| | Coat | 0.02 |
| | Hat | 0.44 |
| Animal | Tiger | 0.36 |
| | Elephant | 0.28 |
| | Pig | 0.21 |